



## Search for Scalar Leptoquarks in the Acoplanar Jet Topology

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A search for scalar leptoquarks has been performed in  $85 \text{ pb}^{-1}$  of data from  $p\bar{p}$  collisions at a center-of-mass energy of 1.96 TeV, collected by the DØ detector at the Fermilab Tevatron. The topology analysed consists of acoplanar jets with missing  $E_T$ . The data show good agreement with the standard model expectations, and mass lower limits have been set for scalar leptoquarks decaying into a quark and a neutrino. Masses between 85 and 109  $\text{GeV}/c^2$  are excluded for a renormalization scale equal to twice the leptoquark mass.

*Preliminary Results for Summer 2004 Conferences*

## I. INTRODUCTION

Topologies involving jets and missing transverse energy have been widely investigated in the past to search for signals of new phenomena in  $p\bar{p}$  collisions. In this note, a search for scalar leptoquarks in the acoplanar jet topology is reported, using  $85\text{ pb}^{-1}$  of data collected at a center-of-mass energy of  $1.96\text{ TeV}$  with the upgraded  $D\bar{O}$  detector during Run II of the Fermilab Tevatron.

Many extensions of the Standard Model (SM) which aim at explaining the apparent symmetry between quarks and leptons predict the existence of leptoquarks (LQ). These new particles are bosons which carry the quantum numbers of a quark-lepton system. They are expected to decay into a quark and a charged lepton with branching fraction  $\beta$ , or into a quark and a neutrino with branching fraction  $(1 - \beta)$ . The search reported in this note concentrates on scalar leptoquarks which decay 100% of the time into a quark and a neutrino ( $\beta = 0$ ).

At hadron colliders, leptoquarks can be pair produced, dominantly by  $q\bar{q}$  annihilation and gluon-gluon fusion. The resulting final state, for  $\beta = 0$ , consists of a pair of quark jets, with missing energy carried away by the two neutrinos. Such topologies have been investigated in Run I, and the current scalar leptoquark mass lower limit is  $98\text{ GeV}/c^2$ [1]. Here and in the following, all limits quoted are at the 95% confidence level.

## II. DATA SAMPLE

For the studies reported in this note, data collected from April to September 2003 have been analysed. The Jets +  $\cancel{E}_T$  trigger used was not available previously in Run II. At the first level, it selects events in which at least three trigger towers record a transverse energy in excess of  $5\text{ GeV}$ . At the second and third trigger levels, requirements are placed on  $\cancel{H}_T$ , the transverse energy missing to the reconstructed jets ( $\cancel{H}_T = |\sum_{jets} \vec{p}_T|$ ). The  $\cancel{H}_T$  thresholds are 20 and  $30\text{ GeV}$  at Levels 2 and 3, respectively.

For the subsequent data selection, it was required that no major component of the detector show any sign of degraded performance. This leaves an available total integrated luminosity of  $85\text{ pb}^{-1}$ . The offline analysis utilizes jets reconstructed with the Run II cone algorithm, with a radius of 0.5 in  $\eta$ - $\phi$  space, appropriately corrected for the jet energy scale. The so-called good jets are further selected by general quality criteria essentially based on the jet transverse and longitudinal profiles.

The sample of  $\sim 7$  million events collected with the Jets +  $\cancel{E}_T$  trigger was reduced to a more manageable size by requiring the following criteria to be satisfied:

- $\cancel{H}_T > 40\text{ GeV}$ ;
- $\cancel{E}_T > 40\text{ GeV}$ ;
- at least two jets;
- $p_{T1} > 40\text{ GeV}/c$ ;
- $p_{T2} > 30\text{ GeV}/c$ ;
- $|\eta_{\text{det1}}| < 1.5$ ;
- $\Delta\Phi < 165^\circ$ ,

where  $p_{T1}$  and  $p_{T2}$  are the transverse momenta of the leading and second leading jets, respectively,  $\eta_{\text{det1}}$  is the leading jet pseudorapidity, assuming that the jet originates from the detector center, and  $\Delta\Phi$  is the azimuthal angle between the two leading jets. Here and in the following, the qualifier “good” in front of “jet” is dropped; it will be restored only in case of ambiguities. Only good jets enter the calculation of kinematic quantities such as  $\cancel{H}_T$  or  $\Delta\Phi$ .

Events in which the presence of obvious calorimeter noise could be detected were rejected, as well as those containing at least one jet not rated as good and with a transverse energy larger than  $15\text{ GeV}$ . The inefficiency of 3.4% associated with these criteria was measured on events selected at random beam crossings (zero-bias events), and also on events collected with an unbiased trigger and containing exactly two jets back-to-back in  $\Phi$  within  $15^\circ$ .

At this point, 38,826 events survive. This sample is still dominated by QCD events with jet transverse energy mismeasurements. Such mismeasurements can in particular be due to a wrong vertex choice, or to cosmic rays showering in the calorimeter. The improved tracking capabilities of the upgraded  $D\bar{O}$  detector can be used to largely reduce these backgrounds.

First the longitudinal position  $z$  of the vertex is restricted to ensure an efficient primary vertex reconstruction:  $|z| < 60\text{ cm}$ . This cut removes 3.9% of the events. Next a comparison of jet energies with their counterparts carried

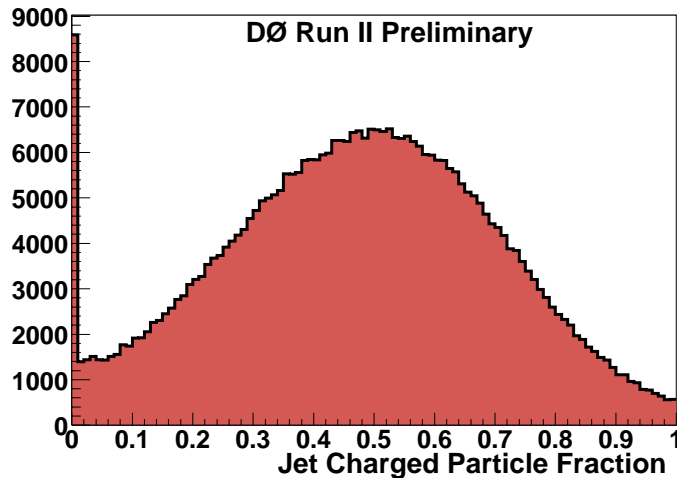


FIG. 1: Distribution of the charged particle fraction CPF for central jets.

by charged particles is performed. The ratio CPF of the transverse energy carried by the charged particles associated with a jet to its transverse energy recorded in the calorimeter is expected to be close to zero either if a wrong primary vertex was selected, in which case it is unlikely that the charged tracks truly associated to the jet will emanate from the selected primary vertex, or if the jet is a fake one, in which case there should be no real charged tracks associated with it. The CPF distribution is shown in Fig. 1 for jets in events selected with an unbiased trigger. A jet is hereafter considered “confirmed” if its CPF is larger than 0.05.

The inefficiency of this jet confirmation procedure was determined using back-to-back dijet events with both jets required to be central ( $|\eta_{\text{det}}| < 1$ ). From the fractions of events with 0, 1, or 2 jets confirmed, it is deduced that the chosen vertex is the correct one in 99% of the cases, and that track confirmation of a jet then occurs at a rate of 98% within  $|\eta_{\text{det}}| < 1$ . It has been checked that this efficiency does not depend on the jet  $p_T$  within the range of interest for the analysis reported in this note.

### III. SIMULATED SAMPLES

Signal efficiencies and non-QCD standard model backgrounds have been evaluated using fully simulated and re-constructed Monte Carlo events, in which the jet energies received an additional smearing to take into account the different resolutions in data and Monte Carlo. The QCD background has not been simulated, and was estimated directly from the data.

#### A. Standard model background simulation

The processes listed in Table I are expected to be the largest contributors to standard model backgrounds in the acoplanar jet topology. They were generated with ALPGEN[2], interfaced with PYTHIA[3] for the simulation of initial and final state radiation and of jet hadronization. The parton density functions (PDF's) used were CTEQ6L and CTEQ5L, depending on the process. An average of 0.8 minimum bias events was superimposed.

The following requirements were imposed at the ALPGEN generator level:

- quark or gluon parton  $p_T > 8 \text{ GeV}/c$ ;
- $\Delta R > 0.4$  for all angles between quarks and/or gluons.

In order to avoid double counting among the various samples, the numbers of jets reconstructed from the generated particles were required to be equal to the corresponding numbers of partons requested whenever a similar sample with higher requested jet multiplicity was available.

TABLE I: Standard model processes, numbers of events generated, cross sections, and numbers of events expected after all cuts. The errors are statistical only.

SM process	events generated	cross section (pb)	events expected
$Z \rightarrow \nu\bar{\nu} + \text{jet jet}$	43 683	144	$20.6 \pm 2.4$
$W \rightarrow \tau\nu + \text{jet}$	49 500	732	$1.0 \pm 0.7$
$W \rightarrow \tau\nu + \text{jet jet}$	32 224	255	$9.6 \pm 2.5$
$W \rightarrow \mu\nu + \text{jet jet}$	188 000	255	$4.3 \pm 0.7$
$W \rightarrow e\nu + \text{jet}$	95 750	732	0
$W \rightarrow e\nu + \text{jet jet}$	189 500	255	$2.9 \pm 0.6$
$Z \rightarrow \tau\tau + \text{jet(s)}$	50 000	72	0
$Z \rightarrow \mu\mu + \text{jet jet}$	188 000	26	0

TABLE II: Numbers of data events selected and signal efficiencies for  $m_{LQ} = 115 \text{ GeV}/c^2$  at the various stages of the analysis.

cut applied	events left	efficiency (%)
Initial cuts	38 826	35.0
<b>C1</b> : leading jet $p_T > 60 \text{ GeV}/c$	31 520	29.0
<b>C2</b> : leading jet $ \eta_{\text{det}}  < 0.8$	20 929	21.2
<b>C3</b> : second leading jet $p_T > 50 \text{ GeV}/c$	9 284	12.8
<b>C4</b> : both leading jet EMF $< 0.95$	9 153	12.8
<b>C5</b> : leading or second leading jet CPF $> 0.05$	7 218	12.8
<b>C6</b> : no electromagnetic object with $p_T > 10 \text{ GeV}/c$	6 994	12.7
<b>C7</b> : no isolated muon with $p_T > 10 \text{ GeV}/c$	6 898	12.7
<b>C8</b> : no isolated track with $p_T > 5 \text{ GeV}/c$	5 970	10.8
<b>C9</b> : no bad jet	4 822	9.6
<b>C10</b> : exactly 2 or 3 jets	1 930	8.1
<b>C11</b> : missing $E_T > 60 \text{ GeV}$	213	6.8
<b>C12</b> : minimum $\Delta\Phi_{(E_T, \text{jet})} > 30^\circ$	74	6.3
<b>C13</b> : maximum $\Delta\Phi_{(E_T, \text{jet})} < 165^\circ$	54	5.8
<b>C14</b> : Optimized cut: $\cancel{E}_T > 70 \text{ GeV}$	44	4.8

## B. Signal simulation

The production of scalar leptoquarks *via* the processes

$$q\bar{q} \text{ or } gg \rightarrow LQ\bar{L}\bar{Q}$$

was simulated with PYTHIA with the CTEQ5L PDF's. An average of 0.8 minimum bias events was overlaid. The chosen leptoquark masses range from 80 to  $140 \text{ GeV}/c^2$ , in steps of  $5 \text{ GeV}/c^2$ . For each mass, 10,000 events were generated, fully simulated, and processed by the same reconstruction program as the data.

The leptoquark pair production cross sections were calculated at next to leading order (NLO) using a code based on Ref. [4], with CTEQ6.1 PDF's[5]. For the mass range considered, they vary from 52.4 to 2.4 pb. The cross section for a leptoquark mass of  $115 \text{ GeV}/c^2$  is 7.3 pb. These values were obtained for a renormalization scale equal to  $m_{LQ}$ .

## IV. EVENT SELECTION

The selection cuts which have been applied in this analysis are listed in Table II, together with the numbers of events surviving at each step and with the evolution of the efficiency for a leptoquark mass of  $115 \text{ GeV}/c^2$ .

The kinematic cuts **C1**, **C2** and **C3** reject a large fraction of the standard model and QCD backgrounds. The purpose of cuts **C4** and **C6** is to reject events likely to contain an isolated energetic electron. (EMF is the fraction of jet energy contained in the electromagnetic section of the calorimeter.) Together with cuts **C7** and **C8**, they reject a large fraction of events originating from the  $W/Z + \text{jet(s)}$  processes. The motivation for cut **C5** has been discussed previously.

The purpose of cuts **C9** and **C10** is to reject QCD background events with fake or real jets in addition to those expected from the signal topology. The inefficiency introduced by the rejection of any bad jets (Cut **C9**) was evaluated in the same way as for the rejection of bad jets with  $p_T > 15 \text{ GeV}/c$ , and was found to amount to 11%.

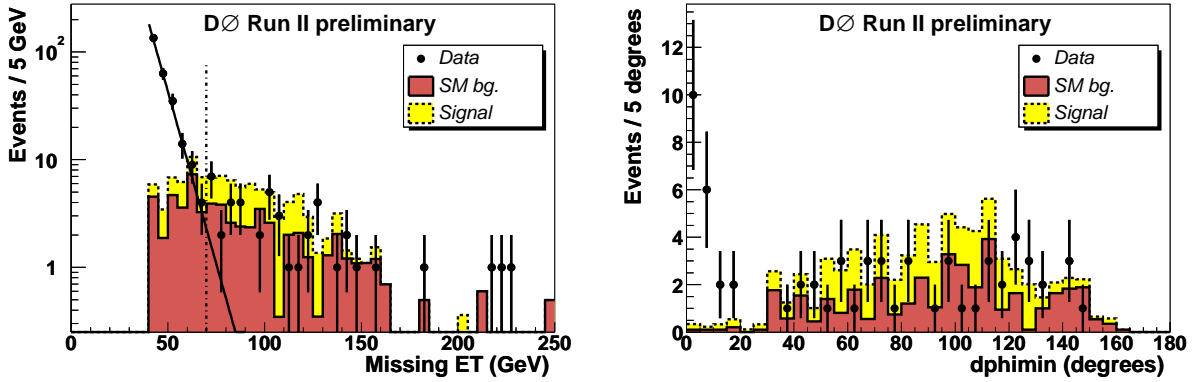


FIG. 2: Distribution of  $\cancel{E}_T$  after all cuts except **C14** and with **C11** relaxed (left) and of the minimum  $\Delta\Phi_{(\cancel{E}_T, \text{jet})}$  after all cuts except **C12** (right) for data (points with error bars), for non-QCD standard model backgrounds (full histogram), and for signal Monte Carlo ( $m_{LQ} = 115 \text{ GeV}/c^2$ ; dashed histogram on top of SM). The fitted QCD background is shown together with the  $\cancel{E}_T$  distribution, as well as the location of the optimized  $\cancel{E}_T$  cut (vertical dashed line).

TABLE III: Standard model, QCD and total backgrounds, and number of data events selected. The errors are statistical only.

SM background	$38.4 \pm 3.7$
QCD background	$3.1 \pm 2.0$
Total background	$41.5 \pm 4.2$
Events selected	44

The inefficiency associated with the rejection of events with more than three jets (Cut **C10**) could be underestimated due to an imperfect modelling of initial and final state radiation in PYTHIA. This effect was evaluated to be at the 1% level, based on studies of jet multiplicities in real and simulated  $Z \rightarrow ee$  events.

Cuts **C11**, **C12** and **C13** are aimed at rejecting QCD events in which the missing  $E_T$  is either moderate, or expected to be correlated with the direction of one of the jets in the event.

Finally, an optimal value of the  $\cancel{E}_T$  cut was determined as the one which minimizes the cross section expected to be excluded for a leptoquark mass of  $115 \text{ GeV}/c^2$ . To this end, it was assumed that the number of events observed is the one expected from background (including the QCD contribution estimated as explained below). The systematic uncertainties discussed further down were taken into account in the calculation of the expected limit. The optimal cut value was found to be  $70 \text{ GeV}$ , which leaves 44 events in the data.

The effect of cuts **C12** and **C14** is shown in Fig. 2 for the data, the standard model background and a typical signal.

## V. BACKGROUNDS

The various standard model background contributions after all cuts are listed in Table I. The main contributor is, as expected,  $Z \rightarrow \nu\bar{\nu} + \text{jet jet}$ . The QCD background was estimated from an exponential fit to the missing  $E_T$  distribution (Fig. 2), in the range  $[40, 55] \text{ GeV}$  and after subtraction of the standard model contribution. The values of the standard model and QCD backgrounds are given in Table III. For  $\cancel{E}_T > 200 \text{ GeV}$  where three events are observed, the background expectation amounts to 1.8 events.

## VI. RESULTS

### A. Signal efficiency

The evolution of the efficiency at the various stages of the analysis is given in Table II for  $m_{LQ} = 115 \text{ GeV}/c^2$ . For the events fulfilling all the selection criteria, the trigger inefficiency is at the level of 1%. The variation of the signal

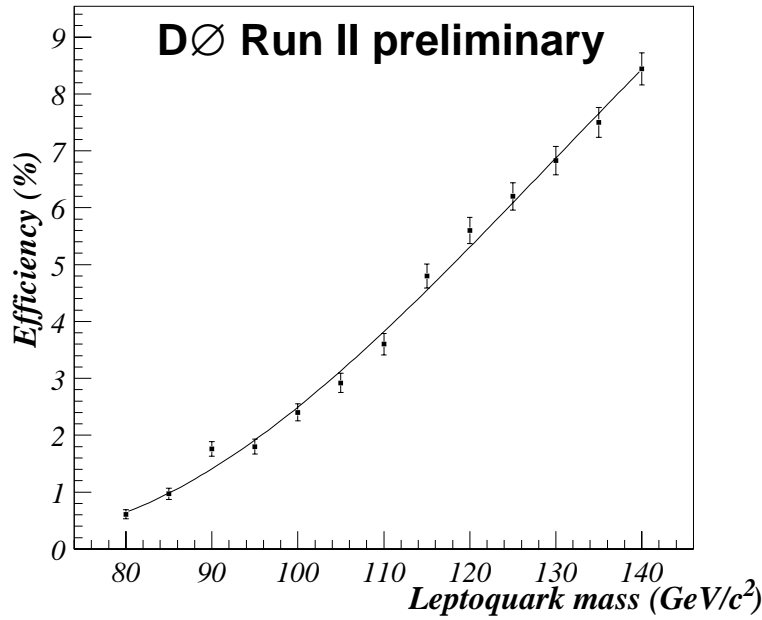


FIG. 3: Selection efficiency as a function of the leptoquark mass. The errors are statistical only. A polynomial parametrization is also shown.

efficiency as a function of the leptoquark mass is shown in Fig.3, together with a parametrization which is used to derive the final results.

### B. Systematic uncertainties

The main experimental systematic errors are fully correlated between signal and standard model backgrounds:

- a 6.5% uncertainty on the integrated luminosity;
- the uncertainties in the data and Monte Carlo jet energy scales. These were added in quadrature and yield a  $^{+13}_{-10}\%$  relative uncertainty on the signal efficiency, and a  $\pm 10\%$  uncertainty on the SM background prediction.

The evaluation of the signal efficiency is affected by the choice of PDF made to generate simulated events. The associated uncertainty was evaluated to be 5%, using a set of modern PDF's.

The systematic errors affecting the SM background cross sections, of the order of 8%, have been estimated by varying in ALPGEN the set of PDF's used and the renormalization scale.

### C. Limits

Given

- the observation of 44 events,
- the background expectation of  $41.5 \pm 4.2$  events,
- the signal efficiency parametrization shown in Fig. 3,
- the above mentioned systematic uncertainties, and
- the integrated luminosity of  $85.1 \pm 5.5 \text{ pb}^{-1}$ ,

cross section upper limits have been obtained as a function of the leptoquark mass, using the  $CL_s$  approach [6] with correlations between systematic errors properly taken into account. The result is displayed in Fig.4.

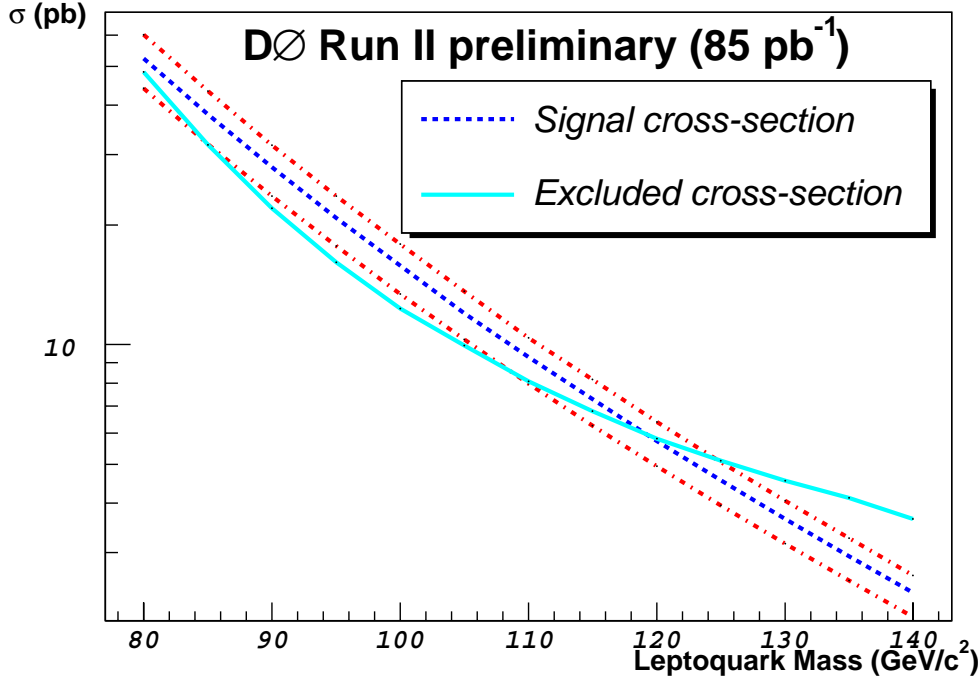


FIG. 4: As a function of the leptoquark mass, 95% confidence level cross section upper limit (light blue; full curve) in pb, and theoretical cross section for renormalization scales equal to  $m_{LQ}$  (dark blue; dashed),  $m_{LQ}/2$  (upper red; dash-dotted) and  $2m_{LQ}$  (lower red; dash-dotted).

In this same figure, theoretical cross sections are drawn for three renormalization scales ( $m_{LQ}$  as central value, and  $m_{LQ}/2$  and  $2m_{LQ}$ ). In the worst case (i.e. a renormalization scale equal to  $2m_{LQ}$ ), the range  $[85, 109] \text{ GeV}/c^2$  is excluded by the present analysis. For a renormalization scale equal to  $m_{LQ}$ , the mass lower limit is  $120 \text{ GeV}/c^2$ . These results improve on previous Run I limits [1].

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